AD/A-004 918

INTERIOR BALLISTICS OF BORE SYSTEMS AND SOLID FUEL ROCKETS

M. E. Serebryakov

Army Foreign Science and Technology Center
Charlottesville, Virginia

1 February 1974

055155

AD A004918

|	
ENGLISH TITLE:	Interior Ballistics of Bore Systems and Solid Fuel Rockets
SOURCE:	Vnulrennyaya ballistika stvol'nykh sistem i porskhovykh raket Moscow, 1962, 249-259, 305-10.
AUTHOR:	Serebryakov, M. Ye.
LANGUAGE:	Russian
COUNTRY:	USSR
REQUESTOR:	TD-Kane
TRANSLATOR:	Leo Kanner Associates, Redwood City, California (DPS)

D D C

RECEIVED

FEB 13 1975

D

ABSTRACT: Propellant grain geometries, burning singularities, advantages and disadvantages are discussed, slotted tube grains in particular detail. Requirements for igniters, several types of igniters, p(t) pressure curves and formulas for calculating igniter weight are presented. Polysulfide, polyurethane rubber and polyhydrocarbon solid fuels, with and without addition of aluminum and magnesium and ammonium perchlorate as the oxidizer are discussed briefly. Increasing specific impulse by use of fluorine and the very light metals is discussed, data on specific impulse of several types of solid fuels are presented and comparative characteristics of solid fuel and liquid fuel launch engines are presented and discussed. Clustered engine systems and methods of assembly and outfitting large engines are listed briefly.
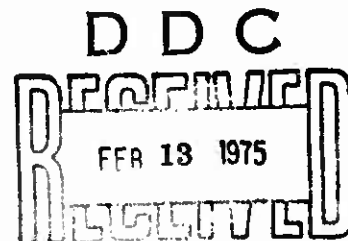
NOTICE

4.2 Propellant Grain Shape

A charge may consist of one or more grains; their forms are extremely diverse.

The caliber of rocket propellants, even in field type projectiles, considerably exceeds the caliber of regular gun propellants. Therefore, they have received the name "propellant grains," although they have the form of thick-walled tubes in the majority of cases.

The highest velocity of a rocket at the end of propulsion flight (at the charge burnout) depends mainly on the energy characteristics of the propellant, the specific impulse I_1, and on the ω/q ratio , the weight of the charge ω to the weight of the remaining portion of the rocket q. The greater ω and the smaller q, the higher the velocity the rocket receives at the end of the propulsion flight. Therefore, the greater the weight of the charge, density of the charge and propellant loading ratio of the chamber, i.e., the ratio of the ratio of the sum of the areas of the ends of the grain nS_e to the chamber cross section F_c, the greater the velocity the engine can provide, under otherwise equal conditions.

Therefore, the question of possibly better loading of the chamber with grains is of great importance for designing a propellant charge.

For tube grains, the outer diameter of the grain D_0 depends on the inner diameter of the chamber D_c:

with 6-7 grains, $D_0 = \frac{1}{3} D_c$,

with 5 grains, $D_0 = 0.37 D_c$,

with 4 grains, $D_0 = 0.415 D_c$,

with 3 grains, $D_0 = 0.464 D_c$.

With one grain, its diameter D_0 can be only a little less than D_c. The propellant loading ratio also depends on the diameter of the grain bore. The maximum

propellant loading ratio, equal to 1, would be obtained with a solid cylindrical grain, without bore, lined with inhibitor on the lateral surface and pressed into the chamber; the charge density Δ would be equal to the propellant density δ. In burning from the end, such a grain retains a constant burning surface; however, in this case, for usual propellants, the gas influx rate would be too small and the engine thrust would be negligible. In order to increase the thrust, the burning rate of the propellant along the grain axis has to be increased considerably.

Therefore, under practical conditions, charges with one or more tubes (single-grain or multi-grain) are used. Besides, there are a great many different shapes. For example, Uimpress gives drawings of cross-shaped grains, which can produce a higher capacity than regular tube grains, but degressive burning results in this case. With the thickness of the bars of the cross about one-third inner diameter of the chamber D_c, the burning surface decreases by 40% at burnout. Therefore, the degree of degressiveness of a grain of such a shape is decreased by completely or partially inhibiting the outer surfaces of all four projections of the grain (Fig. 4.5).
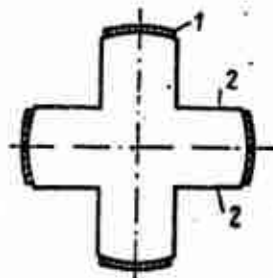

Fig. 4.5: Cross section of cross-shaped grain:
1 - inhibitor   2 - thickness of arch

A partial inhibitor is applied by sections or in a spiral in checkerboard sequence.

Such grains, depending on the relative magnitude of the inhibitor surface, can give p,t curves with various degrees of progressiveness.

Unsatisfactory results of tests (pressure jumps) in a number of cases are explained by insufficient mechanical strength of the propellant grains and instability of the inhibitor. The best method is considered to be inhibiting the ends and 45% of the outer surfaces of the projections; such a grain has the burning surface decreased by 10%.

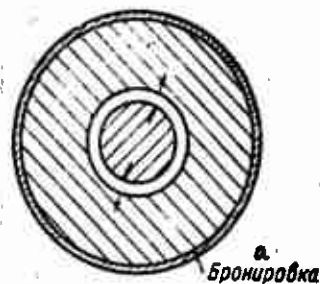Fig. 4.6: Cross section of grain with three projections.

Fig. 4.7: Cross section of telescoping charge.

Key: a. inhibitor

Besides cross-shaped grains, other similar shapes are used. For example, grains with three projections and with inhibited lateral surfaces have an almost constant burning surface during the entire burning process (Fig. 4.6), but they are more complicated to manufacture and they produce more anomalies in burning.

Sometimes, combined telescoping type charges are used, which are rods or round bars, installed with a clearance in the bore of an externally inhibited tube. At a high loading density, such a charge burns with a constant surface -- the tube surface increases and the rod surface decreases (Fig. 4.7).
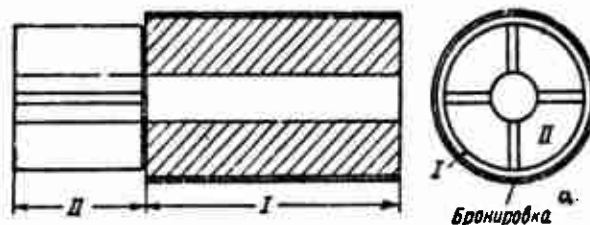
Fig. 4.8: Cylindrical grain with
           longitudinal slots (cuts):

           I - progressively burning portion
               without slots;
           II - degressively burning portion
               with slots.

Key: a. inhibitor

One version of a combined charge (Fig. 4.8) is a tube grain with inhibited outer surface, burning progressively (I), and a tube grain with cross-shaped slots, burning degressively (II). By changing the relative lengths of elements I and II, various deviations from a constant burning surface can be obtained, in the direction of either decrease or increase in total burning surface.

Singularities of Burning of Tube Grains
with Longitudinal Slots

Let us examine more in detail an externally inhibited, tube-shaped grain, with longitudinal slots (slits) in a portion of its length.[1]

At one time in the USA, great attention was given to an externally inhibited, cylindrical grain, with a channel, the cross section of which was star-shaped, with 5 to 16 rays or in the form of the spokes of a wagon wheel.

The advantages of such grains are:

1) When burning, the hot gases do not flow over the surface of the chamber and, therefore, the resulting heating of the chamber walls is at a minimum;

2) The burning surface preserves the minimum propellant thickness almost unchanged for a specific time before burning.

Shortcomings of these grains are:

1) After burning the minimum thickness e_s, breakup of the grain into a number of elements, equal to the number of rays of the stars, begins. These elements of the grain burn degressively with decrease in the burning surface to 0;

2) In manufacture of such grains, the presence of sharp angles and recesses creates a concentration of stresses in the bulk of the propellant, sometimes leading to its cracking in various places, which can cause anomalous burning, with a sharp pressure increase.

The comparatively small thickness of the arches before breakdown occurs ($e_S = (0.20-0.25)D_0$) also is a shortcoming.

Recently, in connection with the development of solid fuel rockets, with great thrust and large caliber, special attention is being given to tube grains, inhibited on the outside and having longitudinal slots (slits) in a certain portion of the grain length. The portion of this grain with a bore and without slots ($n = 0$), with inhibited ends, burns progressively, and the portion of the grain with slots burns degressively and, the larger the number of slots n, the more degressively. Simultaneous burning of both parts of the grain, with definite size ratios, can give an almost constant burning surface.

Among the advantages of grains of this shape are the following:

1) The possibility of obtaining a higher loading density, owing to a decrease in bore diameter;

2) The possibility of obtaining a larger arch thickness ($e_1 = (0.40-0.45)D_0$) and, on this account, of increasing the burning time of the fuel;

[1] Max. W. Stone, "Slotted Tube Grain Design," ARS, 1961, February, p. 223-228.

3) The absence of breakup products, in distinction from charges with a star-shaped bore;

4) Low concentration of stress in the bulk of the fuel, as a consequence of the simplicity of the shape;

5) Simplicity of design of the charge makes its production uncomplicated.

The main shortcoming of this shape is the fact that, for protection of the engine walls from the hot gases in the slot region, a sleeve, a liner of heat-insulating material, must be slipped over this portion of the length of the grain with slots. However, as tests of such charges in the USA have demonstrated, the use of insulating casings does not lead to great difficulties in practice.

For a more graphic idea of the burning of a charge with longitudinal slots, a diagram of this shape of charge is presented below.

A general diagram of a grain with longitudinal slots is depicted in Fig. 4.9. The outer surface and end of the portion of grain without slots is inhibited. In the diagram presented, C is the length of the entire grain; C_n is the length of the portion of the grain with slots (slot length); $C_0 = C - C_n$ is the length of the portion of the grain without slots, where $n = 0$; D_0 is the external diameter of the grain; d_0 is the internal diameter of the grain; $e_1 = (D_0 - d_0)/2$ is the thickness of the burning arches; δ_1 is the slotwidth; $\delta_1/2$ is the radius of curvature of the bottom of the slot.
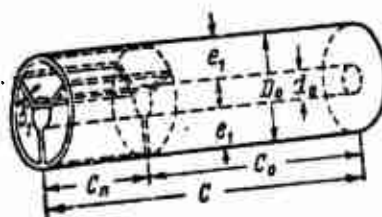

Fig. 4.9: Diagram of grain with three
longitudinal slots.

A cross section of the portion of a grain with slots is depicted in Fig. 4.10; e_1 is the total thickness of the arch, burning in the radial direction; e_s is the thickness of the arch of the sector with slots, burning to burnout perpendicular to the plane of the slot. Depending on the number of slots n and value of the ratio e_1/d_0, the value e_a can be larger than, equal to or less than e_1.

If $e_s > e_1$, burning of the portion of the grain without slots and of the portion of the grain with slots is completed simultaneously, owing to burning of the thickness e_1 in the direction of the radius, which is the smallest in this case. Burning of the charge takes place in one phase in this case.
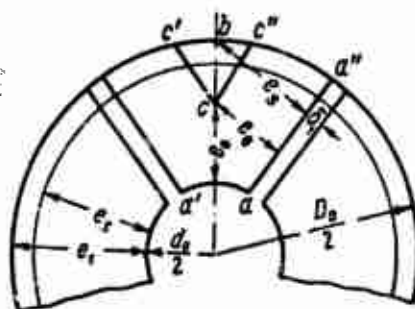
Fig. 4.10: Cross section of grain with
longitudinal slots.

If $e_s = e_1$, burning of the sector along the radius and perpendicular to the plane of the slot ends simultaneously with burning along the radius of the portion of the grain without slots. In this case, burning also proceeds in a single phase.

If $e_s < e_1$, burning of the sector between two slots, at $n \geqslant 4$, proceeds in three phases:

1) From the start of burning to the moment when the cylindrical surface of the portion of the bore between two slots, decreasing, becomes a line (becomes 0); at this moment, the thickness e_0 burns (the distances from point c to the initial surface of the bore aa' and to the planes cf the slots aa'' are identical and equal to e_0). In this first phase, burning of the surface changes according to a single relationship;

2) After burning of thickness e_0, burning proceeds only on the sides of the slots cc'' and cc'; it outstrips burning along the radius, and the projection of the plane of contact of the burning surfaces of the slots goes along the line cb; in this phase, burning of the sectors between slots is more degressive and the surface decreases more rapidly than in the first phase. Second phase burning is terminated when thickness $e_s < e_1$ burns on the sides of both slots;

3) Progressive burning of the remaining portion of the grain without slots, when the surface increases and the ratio $D_0/d_s = D_0/(d_0 + 2e_s)$.

The diagram of burning presented above holds true, if the portion of the grain without slots is separated from the other part of it with slots by an inhibitor and does not burn the end of the portion of the grain with slots.

If this part of the grain with slots is open at the end, during burning of the grain, with decrease in area of the end of it, the height of the part of it with slots C_n decreases; the latter will change according to the relationship $C'_n = C_n$

$(1 - \beta z)$, where $\beta = e_s/C_n$.

The entire lateral surface of the portion of the grain with slots will decrease according to this same relationship.

Consequently, in this case, the initial surface will be larger and the burning will proceed more degressively than with inhibited ends.

If there is no inhibitor between the sections of the grain without slots and with slots, and the slots are cut directly into the integral grain for a length C_n, burning will propagate from the bottom of the slot (flat area $\delta_1 e_1$ or curved area $\frac{\pi}{2} \delta_1 e_1$) deep into the portion of the grain without slots and, by the end of burning on the outer surface, n circular notches with radius $\delta_1/2 + e_1$ form, according to the number of slots. They, intersecting each other, form n scallops. As a consequence of this, the total surface at burnout is decreased, compensating for the increase in burning surface in the third phase.
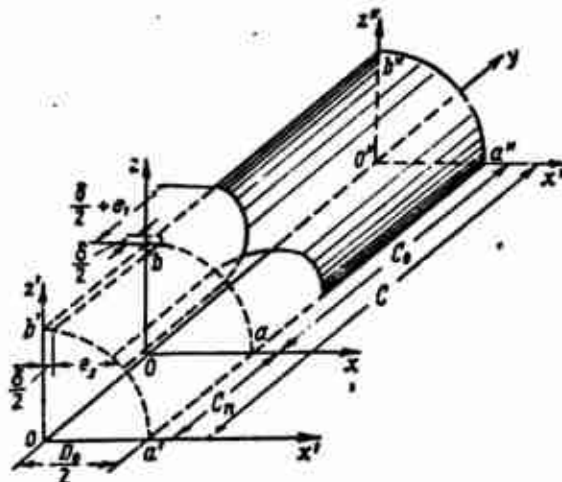

Fig. 4.11: Diagram of burning of grain with
            longitudinal slots, with formation
            of scallops.

The surface at the end of burning of such a propellant with circular scallops is depicted in Fig. 4.11.

Thus, burning of a grain with n longitudinal slots in a portion of its length turns out to be quite complicated and, for analysis of the change in burning surface overall, the pattern of change of each individual surface σ_1 must be found beforehand and which portion a_1 of the total surface each of these surfaces is must be determined. Then, according to the well-known formula (see Chapter 3, page 162)

$$\sigma = \Sigma a_i \sigma_i = a_1 \sigma_1 + a_2 \sigma_2 + a_3 \sigma_3 + \ldots$$

the total change in burning surface is determined.

4.3   Charge Ignition in Rocket Chamber

Ignition of a rocket charge is a complex thermal and physicochemical pro-
cess, in which the following stages can be distinguished:

1) Ignition of igniter;

2) Burning of igniter;

3) Propagation of igniter combustion products along the charge;

4) Heating of the propellant surface and its ignition, by means of the
heat of the igniter gases.

An igniter is used in a solid fuel rocket engine, first, in order to impart
to the surface of the charge the temperature necessary for its ignition and,
second, to create the pressure in the rock chamber, necessary for normal burn-
ing, under conditions of not only feed to,but discharge of,gases through the
nozzle.
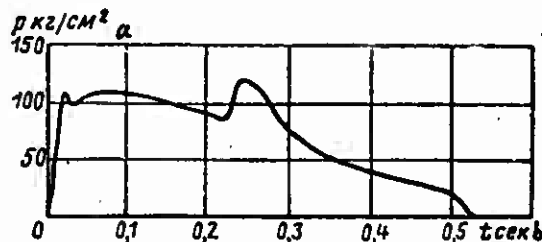
Fig. 4.12:   Diagram of pressure with
            anomalous peak.

Key: a. p,kg/cm^2 b. t, sec

The ignition time should be short and quite stable, and the pressure in
the chamber during charge ignition should not be too high.   In burning, the
igniter should not break up the propellant grains, and its liner should not jam
in the nozzles, which could cause an anomalous increase in pressure (Fig. 4.12).
It usually is located at the bottom of the chamber; sometimes, several igniters
are secured in the bore of the grain (Fig. 4.13).

Fig. 4.13:   Diagram of central igniter
            arrangement:
1 - chsrge;   2 - primary igniter;
3 - supplementary igniters;   4 - fuse.

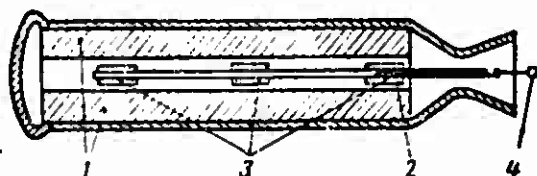There also is interest in igniter design[1]--"rocket in rocket," insuring duration and stability of action of the igniter gases (Fig. 4.14), and a roll igniter, with a pyrotechnic compound (Fig. 4.15).
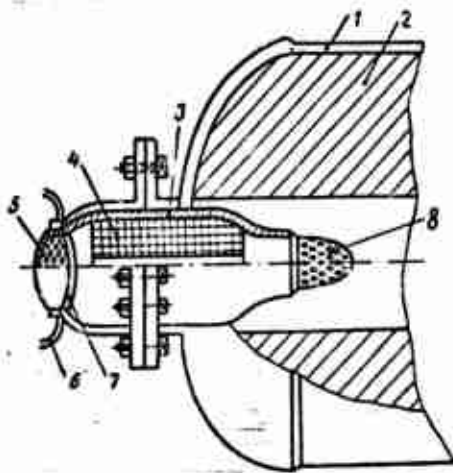
Fig. 4.14: "Rocket in rocket igniter":

1 - rocket casing; 2 - main solid fuel charge; 3 - igniter chamber housing; 4 - high heat value ignition charge fuel; 5 - pyrotechnic compouud grains; 6 - electric fuse; 7 - burnout diaphragm; 8 - reticular tip for escape of igniter gases.
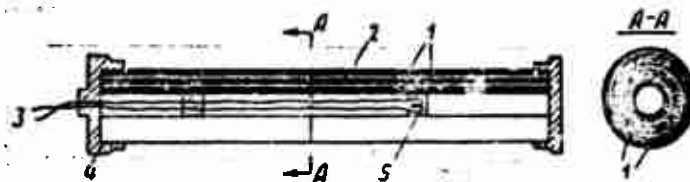
Fig. 4.15: Roll igniter:

1 - sheet of pyrotechnic compound,rolled on central mandrel; 2 - substrate with pyrotechnic compound applied to its surface; 3 - fuse wire; 4 - rubber securing flanges; 5 - electric fuse.

The nature of the igniter and the speed of its combustion have an effect on the initial pressure buildup and on the value p_{max}, which is obtained at the very start of burning of the propellant. With a finely divided black powder igniter, a more abrupt and sharper buildup is obtained on the gas pressure curve than with the same weight of igniter of large-grain powder.

[1]
G. V. Rabern, "Solid Fuel Ignition System," VART, No. 21, 1960.

The igniter charge must satisfy the following requirements:

1) The igniter should rapidly transfer heat to the main charge;

2) The combustion products in the free space should contain a sufficient number of incandescent solid particles to heat the surface of the propellant better and more quickly;

3) The igniter should have a sufficient quantity of gaseous products to rapidly increase the pressure in the rocket chamber to the required value;

4) The igniter charge should be chemically stable during prolonged storage;

5) The igniter should ignite rapidly from the small amount of thermal energy obtained from the fuse.

The black powder which usually is used as the igniter satisfies all these requirements quite well.

Mixtures of potassium perchlorate ($KClO_4$) and aluminum or magnesium also are used for ignition, but they may oxidize these metals during storage. The following are used as ignition compounds: black powder; black powder with metal additives; mixture of metal powder with ground perchlorate type crystals (without fillers); a metal-oxidizer-filler mixture, produced in the form of powders and grains; rapidly burning solid fuel or pressed pyrotechnic compound firecrackers; pyrotechnic compounds applied in the form of a special coating on the burning surface of the main charge; high heat value fuel grains and the like.

Experience in designing and developing various ignition systems has shown that a general requirement is the necessity for insuring contact of the entire burning surface of the main charge with the igniter combustion products and a maximum increase in stay time of the igniter combustion products in the combustion chamber.

During investigation of the comparative ignitibility of various fuels, especially after prolonged storage of charges, it was determined that metallized fuels are more difficult to ignite than fuels, the formulas of which do not contain metal additives; mixed fuels and, especially, those not containing nitrates as the oxidizer, ignite more poorly than ballistite propellants.

For certain mixed fuels, there turns out to be a sharp dependence of the ignitibility on the storage time of the charges; which is explained by disruption of the uniformity of distribution of the oxidizer and fuel components in the body of the grain during storage of such fuels. As a consequence of this, due to a shortage of oxidizer, the surface layer becomes difficult to ignite. This can be overcome by a correct selection of igniter compounds (with an excess of oxidizer in the combustion products).

Up to now, igniters have been selected at the last stage of planning of the motor and have been placed in free spaces of the outfitted combustion chamber,

t it is better to select a place for location of the igniter for each specific charge and engine design.

Tests in a chamber with a nozzle have shown that, during combustion of one igniter in the chamber, the $p(t)$ curve turns out to be in the form of a small peak tent. The more acute it is, the greater the value p_1 and the more finely divided the igniter powder. The igniter gases flow out almost as rapidly as pressure develops.

The area of the $p(t)$ curve of the igniter is insignificantly small, in comparison with the areas of curves obtained during burning of solid fuel grains, and the igniter has an effect on the amount of pressure only in the initial stage of burning of the propellant; after this, the pressure is maintained exclusively by the gases of the charge itself.

Therefore, subsequently, we will not consider the quantity p_1, but only the pressure of the gases of the charge itself in the chamber.

There are many empirical formulas for calculation of the weight of the igniter, which are diverse in composition and in allowing for various factors.

Two formulas can be presented as an example:

$$\omega_1 = 16 \sqrt{\frac{S_1 F_{min}}{\Delta}},$$

$$\omega_1 = \frac{q S_1}{Q_1},$$

where S_1 is the burning surface of the propellant; q is the amount of heat reaching a unit surface of the charge, so as to ignite it reliably ($q \backsim 7$ kcal/kg).

Given igniter pressure p_1 (for example, 50 kg/cm^2) the loading density of the igniter Δ_1, with respect to the initial free volume of the chamber, can be calculated from the Shishkov-Noble formula:

$$\Delta_1 = \frac{\omega_1}{W_0 - \frac{\omega}{\delta}} = \frac{p_1}{f + \alpha p_1}.$$

From this, we determine

$$\omega_1 = \left(W_0 - \frac{\omega}{\delta} \right) \frac{p_1}{f + \alpha p_1}.$$

As is evident, the size of the propellant surface S_1 which must be ignited is taken into account in the first two formulas. Besides this, the smallest nozzle cross section F_{min} and propellant loading density Δ are taken into account in the first of them.

Only the igniter loading density Δ_1, with respect to the initial free space, in order to create the necessary igniter pressure, is determined in the last one.

A marked increase in igniter pressure can very sharply increase the value p_{max} during burning of the charge. Therefore, a correct selection of the igniter weight is an important factor for obtaining a normal $p(t)$ pressure curve.

It should be noted that an increase in igniter pressure affects the buildup value and maximum pressure only at the start of the $p(t)$ curve. After the drop in pressure and drop in buildup, the average pressure is independent of the igniter weight.

4.10 New Types of Solid Fuels for Rockets[1]

Much attention has been given in foreign literature in recent years to the question of new types of solid fuels to replace double-base ballistite propellants, especially for large-size rockets. Among such fuels are mixed solid fuels, which can provide an increased specific impulse I_s of up to 240-250 kg·sec/kg.

Besides, certain of these mixed fuels can be poured directly into the chamber, which permits an increase in loading density.

Beside the two basic nitrocellulose and nitroglycerin propellants, which are used mainly in small-caliber rockets, three types of possible mixed solid fuels, with mineral oxidizer of the ammonium perchlorate type, are now distinguished:

1. Polysulfides, which are used for production of synthetic rubber. They are simultaneously fuels and binders, and they permit bonding of the charge to the case. A deficiency of this type of binder is the fact that the sulfur contained in it is a heavy element ($S = 32$); this increases the atomic weight of the combustion product and decreases the critical gas velocity U_{cr} and, consequently, the specific impulse I_s;

2. Polyurethane rubbers, consisting of C, H_2, O_2 and N_2. The atomic weight of the polyurethane combustion products is significantly less than that of the polysulfides. The physical properties of the polyurethanes are identical to those of the polysulfides;

3. Polyhydrocarbons are a fuel of the ignitible rubber type, used with crystalline oxidizers. This type of fuel is produced by the reaction of an epoxy group, containing two carbon atoms, three hydrogen atoms, and one oxygen atom, with a carboxy group, containing one carbon atom, two oxygen and one hydrogen.

Foreign specialists are expressing the opinion that good results can be expected from the use of "nitro compound plus polyurethane" solid fuels. In the

---

[1] W. R. Maxwell, " Solid rocket boosters," The Aeroplane and Astronautics, 12, 16, 1960, pp. 810-812.

nitro compounds, nitrogen N_2 is bound directly to oxygen O_2 and, in the poly-urethane group, it is bound to carbon C and hydrogen H_2 atoms. It is expected to produce an impulse $I_s > 250$ kg·sec/kg from such nitropolymers.

The are various opinions on the advantages of mixed solid fuels. In parti-cular, it is considered that polyurethanes are especially suitable for large-size engines, because they do not give off a large amount of heat during hardening, after pouring the mass in the form. Their aging characteristics are continually being improved.

Polyhydrocarbons have better qualities at low temperature and long-time aging. These secondary qualities can be decisive, if the range of burning rates is not a significant factor.

Aluminum powder added to solid fuels improves their characteristics. Although its introduction increases the average weight of the combustion products, as a re-sult of formation of aluminum oxide (Al_2O_3), since the burning temperature increases together with this, the overall characteristics of the fuel are improved.

There now is no disagreement whatever among specialists that ammonium per-chlorate (NH_4ClO_4) is the most available, efficient, and cheapest oxidizer.

It also is well-known that the fuel can be improved by means of decreasing the atomic weights of the gases formed during its combustion; this can be achieved, for example, by introduction into the fuel of a large quantity of hydrogen and by decreasing the relatively heavy elements in its composition.

The following considerations might be introduced with respect to the question of how to improve the oxidizer with these items: chlorine Cl has an atomic weight of 35.5; fluorine F, having an atomic weight of 19, can do the same work as chlorine. Of course, ways must be found to use oxidizers with fluorine in solid fuels.

Aluminum Al has an atomic weight of 27. There are three lighter elements with a lower atomic weight, boron B (10.82), beryllium Be (9.0) and lithium Li (6.94), which can do the same work as aluminum. Therefore, precisely these lighter elements should be used in the formulas for solid fuel oxidizers.

Besides, the dissociation ability of the fuel combustion products should be taken into account in making up the fuel formulas. For example, nitrogen N_2, carbon monoxide CO, and hydrogen fluoride HF are completely stable, even at reaction temperatures above 2800°C. However, water vapor H_2O and CO_2 dissociate strongly, dissipating part of the energy in this process, which, as a consequence of this, is not used for increasing the specific impulse. This is still another consideration in favor of introducing a large amount of fluorine into the composi-tion of a solid fuel.

As a result of development of new fuels, solid fuels with a high specific impulse may be obtained, but they are connected with a higher combustion tempera-ture T_0; therefore, existing materials for rocket chamber walls and nozzles may

prove to be insufficiently heat-resistant and, if new chamber materials are not produced, it will be difficult to use the improvement in energy characteristics of the new fuels.

As an illustration of foreign data, the specific impulse I_s in kg·sec/kg of certain types of solid fuels for rockets are presented below.[1]

Cordite	190-210
Double-base cast fuel	190-215
Plastic fuel	170-235
Polyurethane fuel	200-235
Fuel in which ammonium nitrate is used as the oxidizer . . . ., ...	180-220

Comparison of Energy Characteristics of
Solid and Liquid Fuel Jet Engines[2]

The advantages of solid fuel jet engines over the same type of engines using liquid fuel appear particularly graphically in their use for the launch stages of space rockets.

Approximate characteristics of liquid and solid fuel launch engines for space rockets, calculated for certain identical weight parameters of the rockets and identical initial conditions, are presented in Table 4.6, from foreign data.

It is evident from the data in Table 4.6 that solid fuel accelerators have significant advantages over liquid fuel engines.

It has been determined by calculations that, for large space rockets, the optimum value of the ratio of thrust R to launch weight q is 3.5-4.0, and that the G-force at the end of the propulsion flight is not over 8-9. For such thrust-rocket weight ratios, the maximum operating time of the engine is restricted to 60 sec. In this case, a thrust of several hundred tons can be produced only in case consumption per second of the reaction mixtures on the order of tens of tons per second is successfully provided.

For liquid fuel rocket engines, such flow rates are extremely high and to put them into practice requires development of complicated sets of fuel supply systems, which, nevertheless, must be light enough not to impair the overall weight characteristics of the rocket. In a solid fuel engine for this purpose, it is necessary only to plan the fuel load in such a way that the burning surface is adequate to obtain the required gas flow rate and, consequently, the required thrust.

Many already existing high heat value fuels can be used as solid fuels in engines for the purpose being discussed. In this case, a system of charges bonded to the engine housing will be the most efficient.

_____

[1]W. K. Maxwell, "Solid Rocket Boosters," The Aeroplane and Astronautics, 12 16, 1960, p. 810-812.

[2]H. W. Ritchey, Solids, Space Aeronautics, B, D Handbook, 1960-61.

TABLE 4.6: COMPARATIVE CHARACTERISTICS OF TWO TYPES OF LAUNCH ENGINES: SOLID FUEL ROCKET ENGINE AND LIQUID FUEL ROCKET ENGINE

a Характеристики двигателя	b РДТТ	c ЖРД
d Тяга в m	1680	725
e Время работы в сек.	45	125
f Полный импульс двигателя в m·сек	81,650	90,720
g Удельный импульс в кг·сек/кг	249	· 266
h Относительный вес топлива	0,8ζ	0,884
i Максимальная скорость в конце активного участка в м/сек	1990	1620
j Высота подъема в конце активного участка в км	34	50
k Начальное ускорение системы	3,13g	1,31g
l Ускорение в конце активного участка	7,87g	4,02g
m Энергия, сообщенная системе, в m·м	31 500 000	24 700 000
n Тяговый к. п. д.	0,31	0,21

Key:

a. Engine characteristics
b. Solid fuel rocket engine
c. Liquid fuel rocket engine
d. Thrust in tons
e. Operating time in sec
f. Total impulse of engine in ton·sec
g. Specific impulse in kg·sec/kg
h. Relative weight of fuel
i. Maximum speed at end of propulsion flight in m/sec
j. Lift at end of propulsion flight in km
k. Initial acceleration of system
l. Acceleration at end of propulsion flight
m. Energy imparted to system in ton·m
n. Thrust efficiency

With such a charge, the fuel must have an increased resistance to shrinkage and provide sufficient binding strength to the engine housing, allowing for the action of high longitudinal G-forces on the charge. The production of large engines encounters technological difficulties, connected with the manufacture of the engine housing itself and with loading its combustion chamber with fuel.

A comparative evaluation of the physical-mechanical characteristics of high-strength steels, titanium and fiber glass has shown that the most suitable material for the engine housing at the present time is steel. In this case, very large housings, as is indicated in foreign literature, can be manufactured right at the launch position, by means of welding prefabricated, stockpiled sheets of the required thickness.

With the extremely high thrust characteristics of the launch stages of rockets, it is advisable to use a cluster system for engines, in which several rocket engines of acceptable sizes are united. In order to eliminate the eccentricity of the total thrust possible in this case and to decrease the possible time spread in burning of the charges of each of the engines included in the cluster, the engine chambers are interconnected, as a result of which a uniform pressure is maintained in the chambers of these engines during operation.

Methods of Assembly and Outfitting of Large-Size Solid Fuel Jet Engines[1]

According to data in the foreign press, as a result of serious difficulties encountered in transportation of large-size solid fuel jet engines in the USA, methods are being developed for the most efficient loading and assembly of engines at the launch positions.

For loading large-size solid fuel rockets, the following methods are used:

a) Several identical engines are united in a single cluster;

b) The engine is assembled in the launch position from several individual, loaded, short fuel sections;

c) The rocket fuel is poured into the engine housing bore right at the launch position and hardens there.

According to data of the author of the article, H. W. Ritchey, the latter method is considered to be the most promising one.

---

[1] See footnote 2, page 16.